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Wear resistant carbon fiber reinforced Stellite alloy composites

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ABSTRACT

Stellite alloys are a family of cobalt-based superalloys that are the main engineering materials used for severe corrosion, wear and high temperature environments. These alloys are strengthened by various carbides. However, the presence of carbides can cause many problems although they are main agents for wear resistance. This research attempts to develop a class of novel composite materials which substitute carbon of Stellite alloys with carbon fiber, aiming to minimize the disadvantageous effects of carbides in the alloys. Two types of carbon fiber, plain carbon fiber and nickel-coated carbon fiber, are employed in the composites. The new materials are fabricated using hot isostatic pressing (HIP) technique. The microstructures of these composites are analyzed to investigate if any carbides are induced due to incorporating carbon fibers. The tribological properties of these new composites are characterized on a pin-on-disk tribometer. The experimental results show that the developed composites exhibit better wear resistance than that of medium-carbon Stellite alloys and comparable wear resistance to that of high-carbon Stellite alloys.

1. Introduction

Stellite alloys are a group of important industrial materials that display unique combination of excellent corrosion and oxidation resistance, mechanical and tribological properties at both room temperature and elevated temperatures. They are cobalt-based superalloys with the main constituents belonging to the quaternary systems Co–Cr–W–C or Co–Cr–Mo–C. These alloys are generally strengthened by the precipitation of carbides in their cobalt matrix. The most important differences among Stellite alloys are their carbon and tungsten contents, which affect the type and amount of carbide formation in their microstructures. In terms of the volume fraction of carbides, there are two major groups of Stellite alloys: high-carbon alloys such as Stellite 1, Stellite 3 and Stellite 720 for wear resistance and low-carbon alloys including Stellite 21 and Stellite 25 for high temperature and corrosion resistance. In general, the wear resistance increases with the volume fraction of carbides while the ductility improves with lower carbon content [1].

Despite the fact that many types of carbides can improve the tribocorrosion and mechanical properties of Stellite alloys, the existence of carbon in these alloys has its own disadvantages, which can be summarized as formation of unwanted intermetallic compounds and/or carbidic phases [2,3]; oxidation of carbides [4]; transformation of carbides [4]; and inhomogeneous distribution of carbidic phases [4,5]. These disadvantages are more pronounced in the service conditions where wear is accompanied with corrosion and high temperature. Also, the type, size, shape, distribution, and amount of carbides cannot be easily predicted or controlled. This is because the carbide formation process in Stellite alloys is a function of many factors, including alloying element types and fraction, carbon content, fabrication technique, sintering heating and cooling rates, and operational parameters.

To obviate the problems related to the presence of carbides in Stellite alloys, an attempt was made to substitute the main strengthening agent in Stellite alloys, carbon, with carbon fibers in this research. Carbon fibers have very useful engineering properties, including high mechanical properties, good chemical inertness, excellent electrical and thermal conductivities, outstanding thermal stability, and low density [6]. These properties can be readily translated into great flexibility in formulating composites with outstanding specific performance. Two types of carbon fibers, plain and Ni-coated carbon fibers, were employed to create the Stellite alloy composites in this study. The composite specimens were fabricated using the HIP routine. The microstructure and tribological properties of the composites were studied, and they were also compared to those of medium-carbon and high-carbon Stellite alloys. These novel carbon fiber reinforced Stellite alloy composites were expected to replace medium-carbon and high-carbon Stellite alloys in some applications where the side effect of carbides is significant, for example, wear in corrosion and high temperature environments.

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2. Materials and methods

2.1. Specimen fabrication

The matrix material of the new composites is prealloyed Stellite 25 powder. The main reason using Stellite 25 as the matrix is that this alloy contains a very low content of carbon (0.1 wt.%) and thus its microstructure has a very small volume fraction of carbides (<4%). In this case, the effect of carbides in the alloy can be kept as low as possible; on the other hand, the effect of carbon fiber can be pronounced. This alloy also contains 20%Cr, 15%W and 10%Ni (in weight, Co in balance). The prealloyed powder of Stellite 25 had a median particle size ~40 μm. Two types of polyacrylonitrile (PAN)-based carbon fibers were selected as the reinforcement. The first product was plain carbon fiber with 3 mm in length and 0.07 mm in diameter. This product had good processability and good translation of mechanical and electrical properties. The second product was Ni-coated chopped carbon fiber with 6 mm in length and 0.075 mm in diameter. The thickness of Ni layer was about 0.25 μm. The Ni-coating on the carbon fibers was assumed to serve three functions in the composites: (1) to enhance the interface bonding between the carbon fibers and the matrix; (2) to prevent diffusion of carbon from the carbon fibers into the matrix, thus avoiding formation of carbides in the matrix; (3) to alleviate redox reactions including carbon oxidation and carbon reduction at elevated temperatures. The created composite specimens with different carbon fiber contents, together with the pure Stellite 25 specimen, are numbered in Table 1.

The HIP consolidation technique was employed to obtain the specimens. The HIP and sintering temperatures were determined based on the result of differential scanning calorimetry (DSC) analysis on Stellite 25 powder that showed the melting range of this alloy between 1200 °C and 1300 °C. Since for the HIP technique the sintering temperature is usually below the melting point of the material and the powders under sintering are in solidus state, it was determined that all the specimens were HIPed at the temperature of 1150 °C under a pressure of 150 MPa of argon gas for about 2.5 h. The complete sintering cycle is illustrated in Fig. 1.

2.2. Microstructural analysis

The specimens obtained from the HIP process were analyzed microstructurally using an optical microscope. The image in Fig. 2 is the microstructure of specimen A5 (Stellite 25 with 5 wt.% carbon fiber). The main interest of this research was to investigate if there were any carbides induced during the HIP process due to incorporation of carbon fibers. Therefore, the volume fractions of carbides in each specimen were identified and estimated using the image analysis software, Clemex Vision Lite™. As the reference, the carbide volume fraction of pure Stellite 25 specimen was estimated first. The optical image of etched pure Stellite 25 specimen used for this estimation is provided in Fig. 3; the carbide volume fraction was identified and estimated about 3.8%. Similarly, using the image analysis software, the carbide volume fractions of the other specimens were estimated; the results are reported in Table 2.

It is demonstrated that the carbide volume fractions in the composite specimens are slightly more than that in the pure Stellite 25 specimen. Also, the comparison in carbide volume fraction between the composite specimens suggests that the volume fraction of carbides increases with increasing the carbon fiber content in the specimens. These two observations indicate that the diffusion of carbon from the carbon fibers did occur at the high temperatures during the sintering process. However, the amount of carbides induced from the carbon fibers is very small; the maximum carbide volume fraction in specimen A5 (with 5 wt.% of carbon fiber) is only 6.4%. It is worth comparing the carbide volume fraction between Stellite alloys and the carbon fiber reinforced Stellite alloy composites. The volume fraction of carbides in the former varies between 3% and 50% while the carbon content varies between 0.1 and 3.3 wt.% [1,7,8]. However, the volume fraction of carbides in the latter varies only between 4.2% and 6.4% while the carbon (carbon fiber) content varies between 0.25 wt.% in specimen A1 to about 5 wt.% in specimen A5. This implies that employing carbon fiber in Stellite alloys is superior to adding carbon, as viewed from the volume fraction of carbides in the alloys. Therefore, it is reasonable to conclude that the carbon diffusion from the carbon fibers during the sintering process does not significantly affect the volume fraction of carbides in the composites. Regarding the Ni-coating effect on the carbon fibers, it is shown that the carbide volume fractions in all the specimens with Ni-coated carbon fibers are similar and are close to that in pure Stellite 25. In other words, addition of Ni-coated carbon fibers has no significant influence on the carbide volume fraction in the composites. This implies that the Ni-coating on the carbon fibers inhibited carbon diffusion at high temperatures during the sintering process.

2.3. Hardness tests

It is generally accepted that hardness of a material relates closely to its resistance to wear. It is suggested that the harder the material, the more wear resistant it is [9]. In order to correlate the wear resistance with the hardness of these new materials, the hardness of the fabricated specimens was determined on a Wilson Rockwell Hardness Tester in accordance with ASTM: E18-12. The test was conducted using a diamond spheroconical indenter with the force load of 150 kgf. For each specimen, ten hardness measurements were performed and the averages of hardness values were reported as the final hardness values for each specimen.

In addition to overall hardness, in order to investigate the variations of hardness in the local region around carbon fibers in the fabricated composites, thus to further confirm if carbon diffusion

Table 1
Chemical compositions of Stellite alloy composites.

Specimen	Stellite 25 wt.% (vol.%)	Chopped carbon fiber wt.% (vol.%)	Ni-coated carbon fiber wt.% (vol.%)
Stellite 25	100 (100)	0 (0)	0
A1	99.75 (98.8)	0.25 (1.2)	0
A2	99.5 (97.7)	0.5 (2.3)	0
A3	99 (95.5)	1 (4.5)	0
A4	98 (91.4)	2 (8.6)	0
A5	95 (80.4)	5 (19.6)	0
B1	99.75 (99.2)	0	0.25 (0.8)
B2	99.5 (98.4)	0	0.5 (1.6)
B3	99 (97)	0	1 (3)
B4	98 (94.1)	0	2 (5.9)
B5	95 (86.1)	0	5 (13.9)